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A QUANTITATIVE ANALYSIS OF SENSITIVITY TO THE CONDITIONED REINFORCING VALUE OF TERMINAL-LINK STIMULI IN A CONCURRENT-CHAINS SCHEDULE

TAKASHI OMINO

MEISEI UNIVERSITY

Pigeons were exposed to a concurrent-chains schedule in which a single variable-interval 30-s schedule was used in the initial links and fixed-time schedules were used in the terminal links. Three types of keylight conditions were used in the terminal links. In the first condition, different delays were associated with different keylight stimuli (cued condition). In the second condition, different delays were associated with the same stimulus, either a blackout (uncued blackout condition) or a white key (uncued white condition). Paired values of terminal-link fixed-time schedules differed by a constant ratio of 3:1, while the absolute value of delays was varied from 3 s to 54 s. The results showed that choice proportions for the shorter of two delays increased when the absolute size of the delays was increased for all keylight conditions. Further, the choice proportions for the shorter delay increased from the uncued blackout condition, to the uncued white condition, to the cued condition. A modified version of Fantino's (1969) delay-reduction model (expressed as a function relating the response ratio to the delay-reduction ratio) can be applied to these data by showing that sensitivity to delay reduction increased from the uncued blackout condition, to the uncued white condition, to the cued condition. Thus, the present study demonstrated that a modified version of the delay-reduction model can be used to assess quantitative differences in the terminal-link keylight condition in terms of sensitivity to delay reduction (i.e., the conditioned reinforcing value of the terminal-link keylight stimuli).

Key words: choice, delay of reinforcement, conditioned reinforcement, delay-reduction model, terminal-link stimuli, concurrent-chains schedules, key peck, pigeons

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Recent studies of choice with delayed reinforcers have shown that the strength of the terminal-link keylight stimuli as conditioned reinforcers in a concurrent-chains schedule is determined by the terminal-link keylight stimulus conditions signaling delay periods as well as the absolute values of paired delays in the terminal links, when the paired delays differed by a constant ratio (Williams & Fantino, 1978) or by various ratios (Omino & Ito, 1993). For example, Williams and Fantino (Phase 1) examined the effects of the absolute values of paired delays and two types of terminal-link keylight stimulus conditions in a concurrent-chains schedule in which a single variable-interval (VI) schedule in the initial links arranged entry into the terminal links, and the terminal-link keylight stimuli were associated with different delays of reinforcement defined by fixed-interval (FI) schedules. They compared a cued condition with an uncued condition under several pairs of delays, in which the longer delay was twice as long as the paired shorter delay and the absolute values for the longer delays were varied from 10 s to 30 s (e.g., FI 5 s vs. FI 10 s; a constant ratio of 2:1). In the cued condition, choice responses produced different keylight stimuli associated with each delay, whereas in the uncued condition, choice responses produced the same keylight stimulus (i.e., white-key illumination). They found that choice proportions for the shorter delay increased with increases in the absolute values of paired delays in both cued and uncued conditions. They also found that mean choice proportions for the shorter of each pair of delays were higher in the cued condition than in the corresponding uncued condition by an average of 14%.

Similar results were obtained when various ratios of paired delays were used in the terminal links (Omino & Ito, 1993). Omino and Ito (Experiment 1) examined the effects of terminal-link keylight conditions in which entrance into one of the terminal links changed the keylight from white to blackout (the uncued blackout condition) or remained white (the uncued white condition), and the other keylight changed from white to blackout in both conditions. An 8-s (or 16-s) delay to reinforcement was associated with one of the keys, while reinforcer delay values associated

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with the other key were varied from 4 s to 32 s. The results were consistent with those of Williams and Fantino (1978), and showed that choice proportions for the shorter delay increased with increases in the absolute values of paired delays in both uncued blackout and uncued white conditions and that the choice proportions for the shorter delay increased when the terminal-link keylight changed from the uncued blackout to the uncued white conditions. Together with the results of Williams and Fantino, these results indicate that the terminal-link keylight stimulus condition as well as the absolute values of paired delays in the terminal links exert effects on choice.

In describing these conditioned reinforcing effects of the terminal-link keylight stimuli and the effects of absolute values of paired delays in concurrent-chains schedules, two choice models have been suggested; one is the generalized matching equation (Baum, 1974), and the other is a general version of the delay-reduction equation (Fantino & Davison, 1983). When the generalized matching equation was applied to the data obtained by Omino and Ito (1993, Experiment 1), the generalized matching equation described the results, showing that sensitivity to delay ratio was greater in the uncued white condition than in the uncued blackout condition. However, the generalized matching equation cannot deal with the results obtained from the conditions in which paired delays differed by a constant ratio, because the generalized matching equation predicts a constant choice proportion in the constant-ratio conditions.

The delayed-reduction model (Equation 1), originally formulated by Fantino (1969), is applicable to the results obtained under a concurrent-chains schedule in which several conditions of reinforcement delays differ by a constant ratio as well as various other ratios:

$$R_1/R_2 = (T - t_1)/(T - t_2) \quad \text{for } t_1 < T \text{ and } t_2 < T, \tag{1}$$

where T is the expected time to reinforcement from the onset of the initial links, t_1 and t_2 refer to the average delays of the left and right terminal links, and R_1 and R_2 refer to the number of initial-link responses to the left and right alternatives.

The predictions of Equation 1 have been tested in the concurrent-chains procedure with several conditions of reinforcement delay. Evidence supporting the predictions of Equation 1 has been obtained in situations in which the lengths of the initial links are constant and equal while unequal terminal links are lengthened, with the ratio of paired delays held constant across conditions (i.e., "the terminal-link effect"; Fantino & Royalty, 1987; Gentry & Marr, 1980; MacEwen, 1972; Williams & Fantino, 1978). Also, Equation 1 is applicable to the results obtained in situations in which equal initial-link lengths are shortened while paired delays are held constant but unequal (i.e., "the initial-link effect"; Fantino, 1969; Fantino & Davison, 1983; Fantino & Royalty, 1987; Omino, 1991; Wardlaw & Davison, 1974).

The following general version of the delay-reduction model (Fantino & Davison, 1983) can be extended further to the situations in which different types of keylight stimuli are arranged in the terminal links in a concurrent-chains schedule by modifying Equation 1 to a power function:

$$R_1/R_2 = b[(T - t_1)/(T - t_2)]^a \quad \text{for } t_1 < T \text{ and } t_2 < T, \tag{2}$$

where T is the expected time to reinforcement from the onset of the initial links, t_1 and t_2 refer to the average delays of the left and right terminal links, and R_1 and R_2 refer to the number of initial-link responses to the left and right alternatives. Parameters a and b are empirical constants. Equation 2 is equivalent to Equation 1 when parameters a and b are equal to one. If Equation 2 undergoes a logarithmic transformation, we obtain

$$\log(R_1/R_2) = a \log[(T - t_1)/(T - t_2)] + \log b. \tag{3}$$

A bias is present when b is not equal to one. Parameter a represents sensitivity to delay reduction. Parameters a and b can be estimated by applying a linear regression to the log-transformed data of the response ratio and the delay-reduction ratio.

Equation 2 differs from Equation 1 in two significant aspects. First, Equation 2 deals with delay-reduction ratios and obtained response ratios to determine parameters a and b. Second, Equation 2 can accommodate differences in terminal-link keylight stimulus conditions in terms of a as sensitivity to conditioned reinforcing value of the terminal-link keylight stimuli.

The present experiment was designed to test the generality of a modified version of the delay-reduction equation (Equation 2). In order to investigate whether Equation 2 can assess quantitative differences in the effects of terminal-link keylight conditions in a concurrent-chains schedule, the present study employed three types of keylight conditions. In this regard, the present experiment is an extension of the studies by Omino and Ito (1993) and Williams and Fantino (1978).

METHOD

Subjects

The subjects were 4 homing pigeons maintained at approximately 80% of their free-feeding body weights. They had previous experimental histories with concurrent-chains schedules.

Apparatus

A standard experimental chamber (30 cm by 30 cm by 30 cm) with two response keys was used. Each key (2.5 cm in diameter) was transilluminated with white, red, or green light except during a blackout period and operation of the hopper. The keys required a minimum force of 0.10 N to operate. The opening of the hopper that allowed 3-s access to grain was located midway between the two keys and 16 cm below them. Masking noise was provided throughout the experiment by an exhaust fan. A microcomputer system (NEC PC-8801), located in an adjacent room, controlled the experiment and recorded events.

Procedure

Pigeons were exposed to a concurrent-chains schedule in which a single VI 30-s schedule was used in the initial links and fixed-time (FT) schedules were used in the terminal links. The initial links of the concurrent-chains schedule were always initiated with both keys illuminated with white lights. Each value of the intervals for the initial-link VI schedule was derived from the distribution of the Fleshler and Hoffman (1962) series. When each interval timed out, the timer stopped and entry into the terminal link was assigned quasirandomly with equal probability to either the left or the right key (Stubbs & Pliskoff, 1969). In this procedure, each terminal link was presented equally often during each session. The next response on the appropriate key initiated the delay period defined by the value of the terminal-link schedule. For the right key, the delay was always three times longer than the delay on the left key; the terminal-link delays used were either 3 s versus 9 s, 6 s versus 18 s, or 18 s versus 54 s.

To equate overall rates of reinforcement for the two terminal links, the duration of the reinforcement sequence was manipulated for the two keys. The total duration of each terminal link was set at 60 s for all conditions by adding a blackout period after the hopper presentation. The duration of the blackout period was 60 s minus the delay period and the 3-s hopper time. In the 18 s versus 54 s delay condition, for example, the blackout periods were 39 s for the 18-s delay and 3 s for the 54-s delay. Pecking either key during the blackout had no scheduled consequences. At the end of the blackout, the response keys were reilluminated, and the VI timer started again. Each session terminated after 30 reinforcers had been obtained.

Three keylight conditions were arranged in the terminal links. In the uncued blackout condition, entry into either terminal link changed the keylights from white to dark; in the uncued white condition, the keylight just pecked remained white, and the other key was darkened. For the cued condition, entry into one of the terminal links changed the keylight from white to red (or green), and the other key was darkened.

Each condition continued for a minimum of 15 sessions until the following stability criterion was achieved: The choice proportions for the last nine sessions were divided into three blocks of three sessions each. When the means of these blocks differed by no more than 5% and showed no monotonically increasing or decreasing trends, the choice proportion was considered stable. Each condition changed when the stability criterion was achieved.

Table 1 shows the conditions of the terminal-link keylight stimulus, the values of the paired delays, the order of presentation of the conditions, and the number of sessions for each pigeon.

RESULTS

Figure 1 shows the choice proportions for the shorter delay (i.e., initial-link responses for

Table 1

The keylight conditions and values of the FT schedules in the terminal links, the order of conditions, and the number of sessions for each pigeon.

Terminal-link condition			Subject							
	Delays (s)		MP8111		MP8502		MP8808		MP8809	
Keylight stimulus	Left	Right	Order	Sessions	Order	Sessions	Order	Sessions	Order	Sessions
Uncued blackout	3	9	1	15	2	23	4	16	5	21
	6	18	3	15	1	18	5	17	6	15
	18	54	2	16	3	21	6	.15	4	29
Uncued white	3	9	5	18	6	18	3	15	1	15
	6	18	4	16	5	15	1	16	2	15
	18	54	6	16	4	27	2	23	3	16
Cued	3	9	9	16	7	15	8	16	9	15
	6	18	8	20	9	15	9	18	7	16
	18	54	7	17	8	19	7	15	8	15

the shorter delay divided by total initial-link responses) as a function of the paired delays for each pigeon. Data are averaged over the last nine sessions for each condition. In general, choice proportions for the shorter delay increased with increases in the absolute value of the delay. However, the choice proportions differed across the keylight conditions. In the cued condition, the choice proportions were higher than in both uncued conditions for all pigeons; the only exception was for Pigeon MP8502 in the 18 s versus 54 s condition, in which cued and uncued white conditions produced the same choice proportions. The values of the choice proportions in the uncued white condition varied among pigeons: For 2 pigeons (MP8808 and MP8809), the choice proportions in the uncued white condition were similar to those in the uncued blackout condition. In contrast, the choice proportions in the uncued white condition for Pigeon MP8502 were similar to those in the cued condition. When the data were averaged across pigeons in each keylight condition, mean choice proportions in the uncued blackout condition were .61, .68, and .73 for paired delays of 3 s versus 9 s, 6 s versus 18 s, and 18 s versus 54 s, respectively; in the uncued white condition, the choice proportions were .74, .79, and .85, and in the cued condition, the choice proportions were .80, .87, and .92. Thus, the present results reveal that the highest mean choice proportions were obtained in the cued condition and the lowest occurred in the uncued blackout condition.

Figure 2 shows the obtained choice proportions for the shorter delay as a function of the choice proportions predicted by the original form of the delay-reduction equation. The obtained choice proportions were based on data averaged across pigeons for each keylight condition. The dashed line shows perfect matching between the predicted choice proportion and the obtained choice proportion. The obtained choice proportions deviated the most from the predicted choice proportions for the cued condition. The function of the uncued white condition was intermediate between the cued condition and the uncued blackout condition. Consequently, these results indicate that the predicted choice proportions were inconsistent with those obtained from each keylight condition.

Figure 3 shows the logarithm of the ratio of the mean choice responses in each keylight condition as a function of the logarithm of the ratio of the delay reduction. The solid lines are regression lines determined by the least squares method. The values of r^2 show the coefficient of determination. The obtained functions had slopes of 0.39 for the uncued blackout, 0.51 for the uncued white, and 0.78 for the cued conditions (Figure 3). In other words, sensitivity to delay reduction increased from the uncued blackout condition, through the uncued white, to the cued condition, because the slopes in each regression line represent sensitivity to delay reduction. Biases, on the other hand, did not change systematically from the uncued to the cued conditions.

DISCUSSION

The present results confirmed previous findings that choice proportions for the shorter of

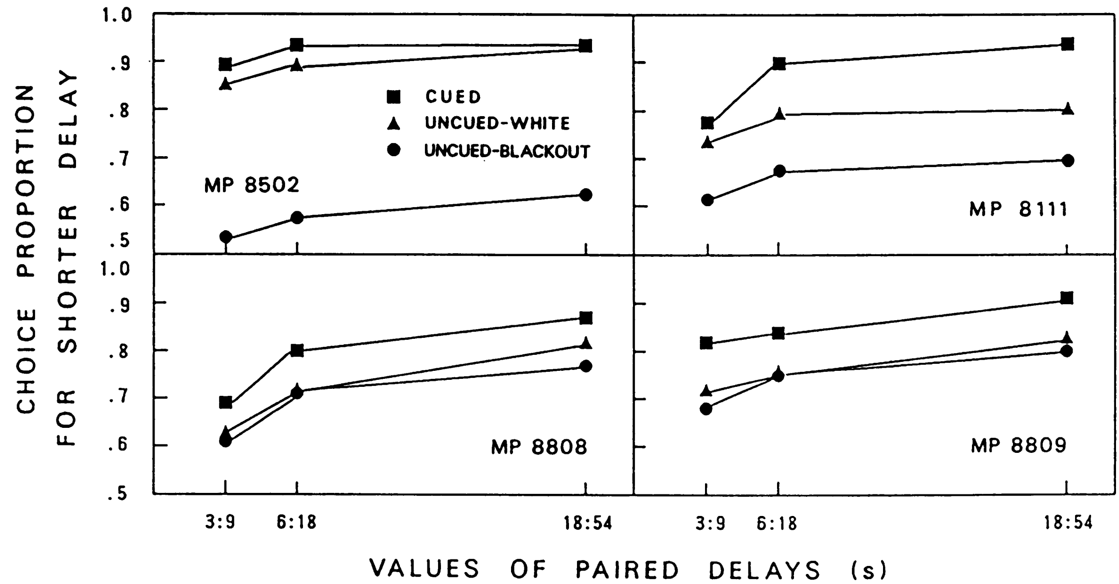

Fig. 1. Choice proportions for the shorter of two delays as a function of the values of paired delays for each pigeon. Squares, triangles, and circles represent the data obtained from cued, uncued white, and uncued blackout conditions, respectively.

two FT schedules with a constant ratio of paired delays increased as a function of the absolute values of the FT schedules (Gentry & Marr, 1980). Similar results were also obtained in other conditions in which a constant ratio of paired delays was defined by the FI schedules (e.g., MacEwen, 1972; Williams & Fantino, 1978). Related studies of terminal-link schedules, in which various ratios of paired delays were used (Neuringer, 1969; Omino & Ito, 1993, Experiment 2), showed that choice proportions were not affected by the difference in response dependency in the terminal-link schedules (i.e., FT vs. FI schedules).

The present results are consistent with previous findings that choice proportions for the shorter delay increased from the uncued blackout condition through the uncued white to the cued condition (Omino & Ito, 1993). For example, Omino and Ito (Experiment 2) examined the effects of terminal-link keylight conditions using only one ratio of delay intervals, in which the longer delay was twice as long as the shorter delay (i.e., 8 s vs. 16 s or 16 s vs. 32 s). Three types of keylight conditions, each of which corresponded to the uncued blackout, uncued white, and cued conditions in the present study, were arranged in the terminal links. The experiment was conducted in a replication design; to correct for order effects of the keylight stimulus conditions, a reversed sequence of each keylight condition was arranged. The results obtained from the replication design were consistent with those of the present study; the uncued white condition increased the choice proportions by an average of 17%, and the cued condition increased the choice proportions by an average of 26% from a baseline condition (i.e., uncued blackout). Together with the results of Williams and Fantino (1978) and Omino and Ito (1993), the present results indicate that the terminal-link keylight stimulus condition differentially exerts its effect on choice as a conditioned reinforcer in the concurrent-chains procedure. In this regard, Omino and Ito discussed differences in the conditions of the keylight stimuli signaling the two terminal-link schedules, and concluded that the conditioned reinforcing effect of the stimuli was greater in the cued than in the two uncued conditions.

To examine the generality of the generalized delay-reduction model, Equation 2 was applied to the data obtained in other studies in which a constant ratio of paired delays was used (Gentry & Marr, 1980; Williams & Fantino, 1978) or various ratios of paired delays were used (Omino & Ito, 1993). The data from Williams and Fantino (Phase 1) are means of the response ratios at each delay pair over a

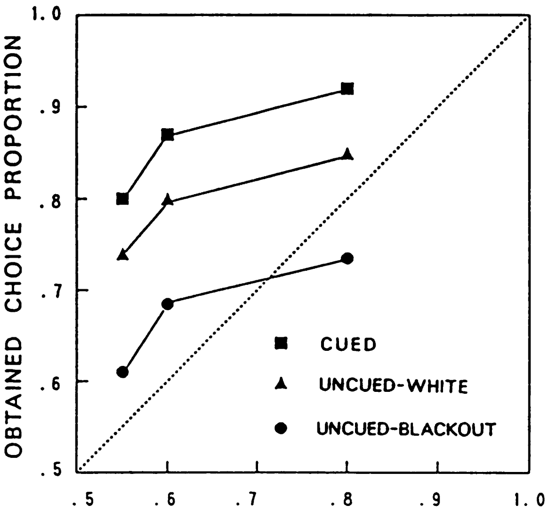

Fig. 2. The obtained choice proportions for the shorter delay as a function of the choice proportions predicted by the original form of the delay-reduction equation (Fantino, 1969). The obtained choice proportions were based on the data averaged across pigeons in each keylight condition. The dashed line represents a perfect match between obtained and predicted choice proportions.

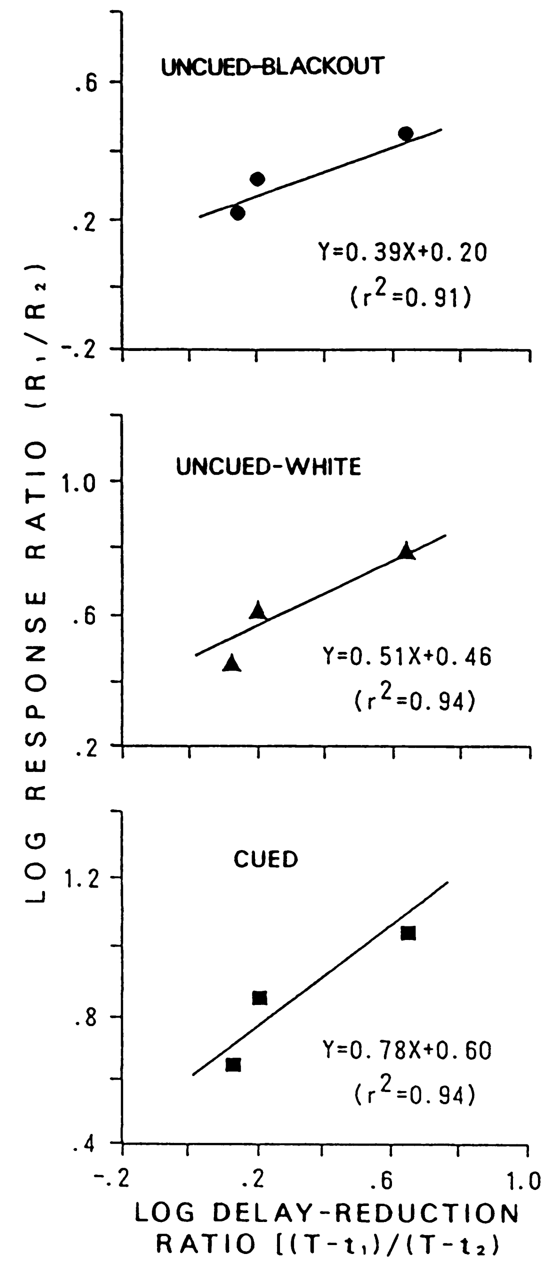

Fig. 3. The log response ratio as a function of the log delay-reduction ratio in uncued blackout, uncued white, and cued conditions. Data are averaged across pigeons in each condition. The solid lines show least squares fits to the data.

range of 5 s to 30 s. The data from Gentry and Marr are means of response ratios over a range of 1 s to 32 s (the data obtained from the paired delays of 16 s vs. 32 s and 32 s vs. 128 s conditions were eliminated because these conditions showed extreme preference for the shorter delay). As shown in Figure 4, Equation 2 provides a close fit to the data obtained with constant ratios of paired delays. Percentages of data variance accounted for ranged from 97% to 99%. Furthermore, Equation 2 can accommodate the differences in the terminal-link keylight stimulus conditions, showing that the uncued white condition and the cued condition increased the value of *a* (i.e., sensitivity to delay reduction) relative to the uncued blackout condition. As for the condition with various ratios of paired delays, the data from Omino and Ito (1993, Experiment 1) are means of the response ratios at each delay pair over a range of 4 s to 32 s. The present analysis also reveals that values of sensitivity to delay reduction in each function increased from the uncued blackout to the uncued white conditions even for the condition with various ratios of paired delays.

To see whether the condition with the ratio of paired delays affects the sensitivity values, the obtained function in the constant-ratio condition was compared with that of the various-ratios condition. For the uncued blackout condition, the sensitivity values in the constant-

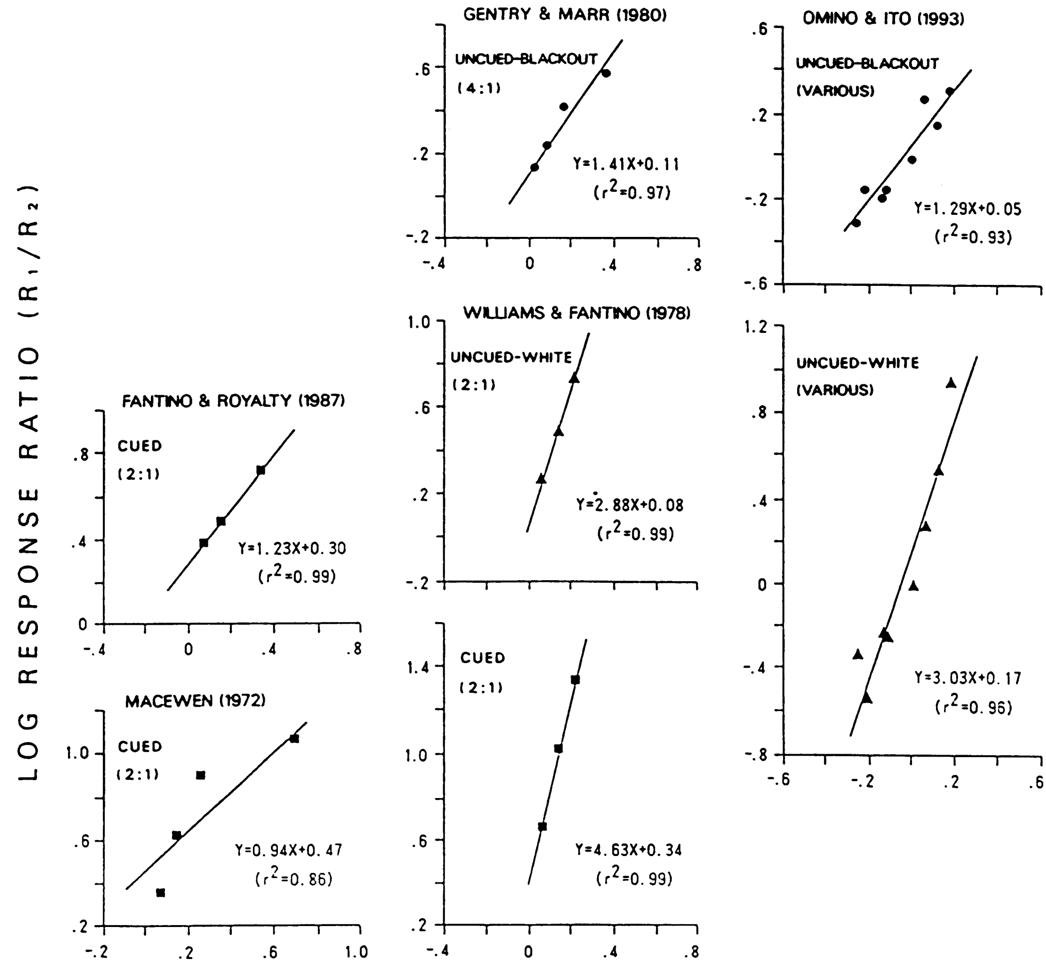

Fig. 4. The log response ratio as a function of the log delay-reduction ratio. Data are obtained from other studies (Fantino & Royalty, 1987, Conditions 4, 5, and 6; Gentry & Marr, 1980; MacEwen, 1972; Omino & Ito, 1993, Experiment 1; Williams & Fantino, 1978, Phase 1). The data are averaged across pigeons in each study. The solid lines show least squares fits to the data. The ratios of paired delays are presented in parentheses.

ratio condition (i.e., Gentry & Marr, 1980) were similar to those in the various-ratios condition (i.e., Omino & Ito, 1993). For the uncued white condition, similar trends in sensitivity values were also obtained between the constant-ratio (i.e., Williams & Fantino, 1978) and the various-ratios (i.e., Omino & Ito, 1993) conditions. Therefore, the present analysis suggests that the ratio of paired delays did not affect sensitivity values when the values of delays ranged from 1 s to 32 s in each keylight stimulus condition.

However, it appears that absolute values of delays may affect sensitivity to the conditioned reinforcing value when a constant ratio of paired delays is used. Equation 2 was applied to the data obtained by Fantino and Royalty (1987, Conditions 4, 5, and 6) and MacEwen (1972), in which a constant ratio of 2:1 was used in the cued condition. The data from these studies are means of the response ratios at each delay pair over a range of 5 s to 90 s. The sensitivity value obtained by Fantino and Royalty was similar to that of MacEwen, but lower than that of Williams and Fantino (1978) in the cued condition. The same conditions of a constant ratio of paired delays (i.e., 2:1) and the keylight stimuli (i.e., cued condition) were used for these studies, but Fantino and Royalty and MacEwen used absolute values of delays approximately three times as long as those of Williams and Fantino. Therefore, the present analysis demonstrates that the sensitivity values for the cued condition with a constant ratio of paired delays decreased when the absolute values of paired delays increased above 30 s (i.e., Williams & Fantino, 1978) to 90 s (i.e., Fantino & Royalty, 1987; MacEwen, 1972).

An interaction between size of ratios and absolute value of paired delays may also affect sensitivity to the conditioned reinforcing value of the keylight stimuli. Although results of the present study are consistent with those of Williams and Fantino (1978), the sensitivity value in the uncued white condition in the present study was lower than in the corresponding condition of the Williams and Fantino study. The present study used a larger paired delay ratio and longer values of paired delays (i.e., a constant ratio of 3:1 with the values of paired delays ranging from 3 s to 54 s) than did Williams and Fantino (i.e., a constant ratio of 2:1 with the values of paired delays ranging from 5 s to 30 s). Thus, it seems that the interaction between ratio size and absolute values of paired delays is another factor that affects the sensitivity values for the terminal-link keylight stimuli. The present analysis reveals that this interaction between larger size of the delay ratio and longer values of delays lowered sensitivity to the conditioned reinforcing value of the terminal-link keylight stimuli.

In any case, the present study demonstrates that Equation 2 is a general model of choice in a concurrent-chains schedule in that it can accommodate differential effects of the terminal-link keylight stimulus condition as well as the absolute values of paired delays in terms of a (i.e., sensitivity to delay reduction). The present analysis reveals that the sensitivity values differed in the terminal-link keylight conditions, and were affected by absolute values of paired delays and/or an interaction between size of ratios and absolute values of paired delays.

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